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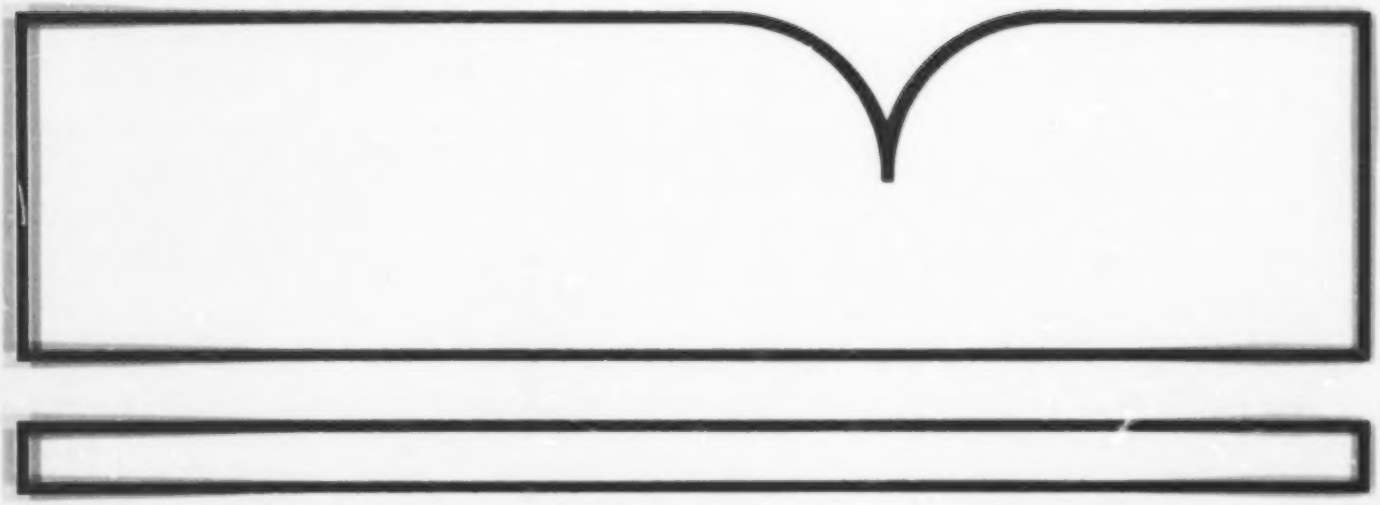

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ESTIMATING SURFACE CONCENTRATIONS FROM AN ELEVATED, BUOYANT PLUME IN A LIMITED-MIXED CONVECTIVE BOUNDARY LAYER

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16. ABSTRACT

In the past decade, recent advances have suggested that convective scaling can be used to parameterize diffusion from a plume in the convective boundary layer (CBL). New methods such as convective scaling need to be explored because the traditionally used Gaussian plume model does an especially poor job in predicting diffusion from an elevated, buoyant plume in the CBL.

Briggs (1985) introduced a formula based on convective scaling for estimating surface concentrations from elevated, buoyant plumes in the limited-mixed CBL. Briggs strongly recommended that the formula be tested against additional field data.

Diffusion data from the Kincaid field experiment (sponsored by Electric Power Research Institute) was used in the analysis. The results show that the Briggs' formula outperforms a Gaussian plume model.

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1. INTRODUCTION

Deardorff and Willis (1984), Briggs (1985), Weil (1985) and Irwin et al. (1985) have suggested that convective scaling can be used to parameterize surface concentrations from a bouyant plume in the convective boundary layer (CBL). New methods such as convective scaling need to be explored because the traditionally used Gaussian plume model does an especially poor job in predicting diffusion from an elevated, buoyant plume in the CBL. In fact, Deardorff and Willis (1984) have observed that vertical distributions of an elevated plume do not follow a Gaussian distribution, and that buoyant plumes tend to "bump" against an elevated inversion resulting in increased horizontal dispersion over that predicted with PG dispersion curves.

Briggs (1985) introduced a formula for estimating surface concentrations from elevated buoyant plumes in the limited-mixed CBL. Briggs' equation is based on two important dimensionless quantities: non-dimensional downwind distance, X, and plume buoyancy, F*. Briggs related the non-dimensional surface crosswind-integrated concentration, Cy, to F* and X by the following expression:

$$C_y = \exp(-(7F_*/X)^{3/2}) \qquad (1)$$

where $C_y = z_i u \int \chi dy/Q$, $F^* = F_b/(uw^{*2}z_i)$, and $X = (x/u)(w^*/z_i)$, where z_i is the mixing height, u is the averaged wind speed in the CBL, Q is the emission rate, F_b is the buoyancy flux parameter, w^* is the convective scaling velocity, and x is the downwind distance. The centerline concentration, χ_c, can be derived from Eq. 1 as follows:

$$\chi_c = 0.25\ Q(\exp(-7F_b/(xw_*^3))^{3/2})/(F_b^{1/3}x^{2/3}z_i) \qquad (2)$$

While the above expression is relatively easy to apply, Briggs has strongly recommended that it be tested against additional field data.

In this paper, we examine the predictive capability of Briggs' expression and an EPA regulatory model for estimating ground-level concentrations from an elevated bucyant plume in the limited-mixed CBL. This evaluation will be accomplished by looking at data from the Kincaid power plant taken during an EPRI-sponsored field experiment.

2. DATA

EPRI's Plume Model Validation Experiment (Bowne et al., 1981) involved intensive field measurements around the Kincaid power plant during the summers of 1980 and 1981. Kincaid is located in central Illinois (latitude 39°N, longitude 90°W) at an elevation of 182 m above sea level. Approximately

100 hours of data were collected during daytime, convective conditions. The tracer release portion of the study was unique in that SF_6 was injected directly into the 187 m stack so that diffusion measurements could be made of an elevated bouyant plume.

Extensive meteorological and tracer measurements were taken during the study. Meteorological data were collected from an instrumented 100 m tower, hourly airsonde releases, and a Doppler acoustic sounder. For this paper, mixing heights were determined from hourly on-site temperature soundings since most periods studied involved mixing heights that were near or above the detection limit of the acoustic sounder which was approximately 600 m. Sampling arcs for hourly measurements of SF_6 concentrations were established according to the predicted wind direction and stability class. Typically during unstable conditions, samplers spaced about three degrees apart were placed along arcs at downwind distances of 3 km, 5 km, 7 km, 10 km, and 20 km. Generally, over 200 samplers were used during an intensive measurement period. For further details on the field experiment, the reader is referred to Bowne et al. (1981).

For this paper, five days of intensive measurements were examined. Three days were selected that represented convective conditions when the plume probably bumped against the inversion but did not penetrate into it. The criterion used for selecting these periods was for F* to range from 0.09 to 0.9. For F* values less than 0.09, the plume is not expected to interact with the elevated inversion before surface impaction. For F* values greater than 0.9, substantial plume penetration can occur. Another criterion used in the selection was to include those hours when u/w_* was less then 6. This corresponds to free-convective similarity scaling conditions as defined by Deardorff and Willis (1975).

The meteorological and source data for the three days are summarized in Table 1. Values of the convective scaling velocity, w*, were estimated using the method for determining the sensible heat flux described in Holtslag and van Ulden (1983).

3. ANALYSIS

The objectives of the analysis were twofold. First, we examined non-dimensional cross-wind integrated concentrations as predicted with the Briggs formula and compared them with observed data. Second, we compared observed centerline concentrations with the Briggs formulation and an EPA regulatory model, MPTER (Pierce and Turner, 1980).

To compare the observations against the Briggs equation, the data had to be non-dimensionalized into C_y and X/F^*. The crosswind integrated concentration needed for C_y was determined from a weighted-average concentration at each sampler to account for small deviations from the average radial distance.

Figure 1 shows a comparison of the Briggs equation with the observed data. In general, the Briggs equation represents an upper-limit to the observations. The equation agrees fairly well with observations at X/F^* values greater than about 70, but it overpredicts by at least a factor of two at smaller X/F^* values. The good comparison at larger X/F^* values is not too surprising as these X/F^* values correspond to downwind distances where uniform mixing is expected and the C_y values should approach unity. The C_y values less than unity at these distances could be caused by either plume penetration or the failure of the arcs to sample all of the plume. However, care was exercised in the analysis to omit cases when either of these effects were likely. The observations for small X/F^* values are about 50% lower than the Briggs equation. This would suggest that the plume is descending to the surface slower than what is predicted by Briggs. However, it should be noted that errors in X/F^* are extremely sensitive to errors in w^*. In fact, errors in w_* are magnified by a factor of three in X/F_*.

Although errors in w_* may account for some of the scatter in Fig. 1, other scaling parameters merit consideration. We examined median values of F_* for the three days but found very little evidence of a systematic variation in X/F_* values due to changes in F_*. Other scaling parameters, such as z_i/L warrant further investigation. Meanwhile, caution should be used before attempting to fit a better curve to the observed data in Figure 1.

The second phase of the analysis involved looking at the actual concentrations from the perspective of the regulatory modeler. To accomplish this comparison, observed and modeled concentrations from the three days of data were paired in space and time and plotted on scatter diagrams. Wind direction was not considered in the analysis other than to assume that the wind blew the plume directly over the sampler showing the highest concentration along an arc. With the Briggs model, centerline concentrations were predicted using the estimated cross-wind integrated concentration and by assuming that $\sigma_y = 1.6 z_i F_*^{1/3} X^{2/3}$ as suggested by Briggs (1985). With the MPTER model, onsite meteorological data as shown in Table 1 were used to predict ground-level centerline concentrations.

Scatterplots for the two models are shown in Figures 2 and 3. The MPTER model run resulted in several hours of zero concentrations because it assumes that the plume either lofts completely above the mixed layer or remains trapped below it. Statistics from the scatterplots are given in Table 2. It is noteworthy that concentrations from the Briggs model have a correlation of 0.73 with the observed data while the MPTER model correlation is only 0.25.

While the performance of the Briggs model is encouraging, the model predictions should be diagnosed in more detail to uncover any problems or limitations with the equation. Given the space limitations of this paper, we can only look at the ratio of predicted over observed centerline concentrations as a function of non-dimensional distance, X. For this comparison, the fractional error was used because it is logarithmically unbiased. The fractional error (FE) is computed from the modeled concentration (M) and observed concentration (O) as follows:

$$FE = 2(M-O)/(M+O). \qquad (3)$$

In Eq. 3, a value of 66.67% corresponds to an overestimate by a factor of two, and a value of -66.67% corresponds to an underestimate by a factor of two. Figure 4 shows fractional errors ranging from -199% to 141% at small X, but the fractional errors quickly approach zero at larger X. Although there is a good amount of scatter at small X, the Briggs model tends to overpredict the centerline concentration for X values less than about 4. This corresponds to the model performance noted in Figure 1 with the non-dimensional crosswind-integrated concentrations.

As a final check on the validity of using convective scaling, we have plotted observed non-dimensional concentrations, $C = \chi z_i^2 u/Q$, as a function of X for F* values around 0.11. The plot shown in Figure 5 shows good agreement with towing tank data behavior as plotted in Figure 6 of Deardorff and Willis (1984), but median values are about 40% lower. The scatter from the observations shown in Figure 5 can be partially attributed to the stochastic nature of the convective boundary layer.

4. SUMMARY

Modeling the diffusion of a buoyant plume in a limited-mixed CBL has frustrated air quality modelers for decades. However, recent ideas in convective scaling offer some hope for improvement.

Observations from the Kincaid field experiment show reasonable agreement with predictions from the equation suggested by Briggs. Use of a Gaussian model for limited-mixed convective conditions generally resulted in significant over and underpredictions. The Briggs equation tends to overpredict ground-level concentrations close to the source suggesting that the plume is not being diffused downward as quickly as is indicated with his formula. Additional analysis of data is planned to investigate the tendency of the equation to overpredict at small X/F* values.

Future work is also planned for examining plume diffusion during convective conditions involving significant penetration into the elevated inversion and involving smaller values of F*.

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Disclaimer

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Table 1. Summary of meteorological, source and receptor data from the Kincaid field experiment.

Day	Hr	u (m/s)	PG class	z_i (m)	F_b (m^4/s^3)	w* (m/s)	F*	Q (kg/hr)	Approximate arc distances (km)
7/13/80	13	1.8	A	450	497	1.4	.31	52.6	2,4,5,7,11
	14	2.1	B	500	568	1.4	.28	47.6	4,6,7,10
	15	1.8	B	550	562	1.3	.34	47.6	1,4,6,7,11
	16	2.2	B	600	559	1.1	.35	48.5	4,6,7,11
	17	2.1	B	600	561	0.8	.70	51.3	2,6,8,11
7/24/80	11	3.1	A	1600	2210	2.2	.09	46.3	1,3,5,16,20
	12	3.1	A	1600	2243	2.3	.09	47.2	1,4,5,16,21
	13	3.1	A	1600	2273	2.2	.09	47.6	1,3,7,16,21
	14	2.4	B	1700	2304	2.3	.11	48.5	1,3,5,16,21
	15	2.2	B	1800	2405	2.2	.13	49.4	1,3,5,8,16,20
	16	1.9	B	1700	2338	1.9	.20	49.9	1,4,5,8,16,21
5/15/81	10	6.8	C	430	1117	1.5	.17	57.2	3,5,10,20
	11	4.9	B	480	1146	1.6	.19	54.4	3,5,10,20
	12	4.4	B	560	978	1.7	.14	57.6	3,5,10,20
	13	4.3	B	760	965	1.8	.09	63.5	3,5,10,20

Table 2. Comparison of the Briggs and MPTER models for predicting centerline, ground-level hourly SF_6 concentrations.

Parameter	Briggs	MPTER
Mean concentration (n=68) (observed = 134.9 ppt)	150.1 ppt	40.3 ppt
Percentage of predictions within a factor of two of the observations	75%	15%
Pearson correlation coefficients (observations and predictions paired in space and time)	0.73	0.25
Line of best-fit Y = model conc. (ppt) X = observed conc. (ppt)	Y = 0.88X + 30.9 ppt	Y = 0.23X + 9.1 ppt

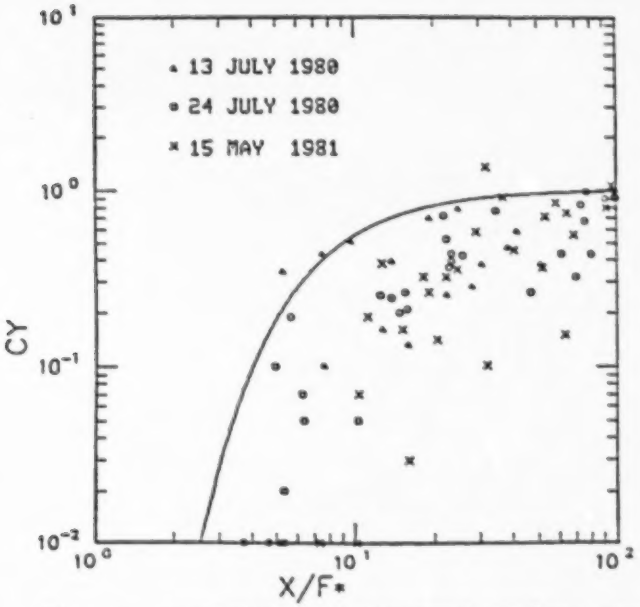


Fig. 1. Comparison of observed surface non-dimensional cross-wind-integrated concentrations, C_y, with the Briggs (1985) equation. Solid line represents the Briggs equation which is $C_y = \exp(-(7F^*/X)^{3/2})$.

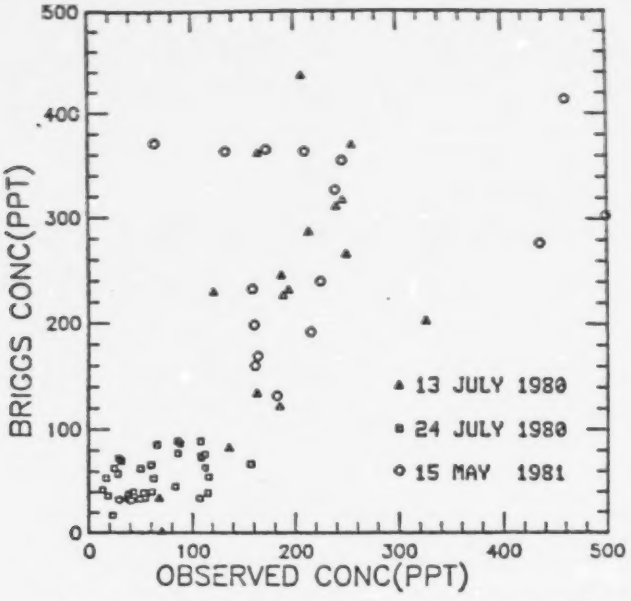


Fig. 2. Comparison of observed centerline ground-level SF_6 concentrations from Kincaid with predictions from the Briggs equation.

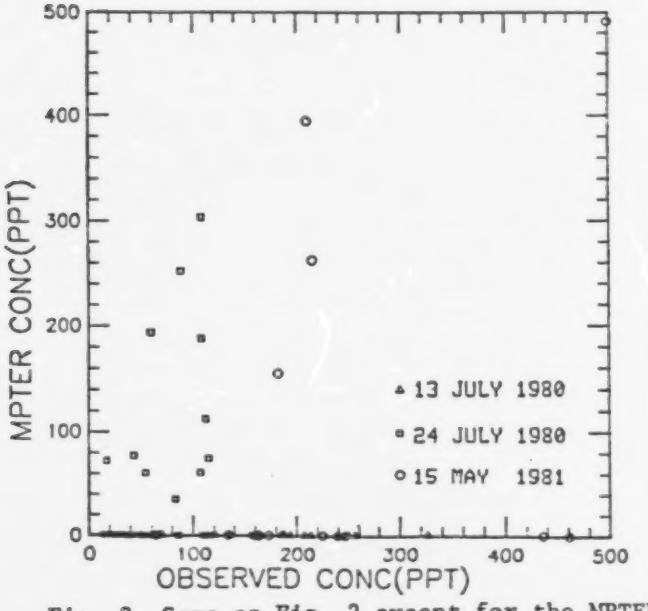


Fig. 3. Same as Fig. 2 except for the MPTER model.

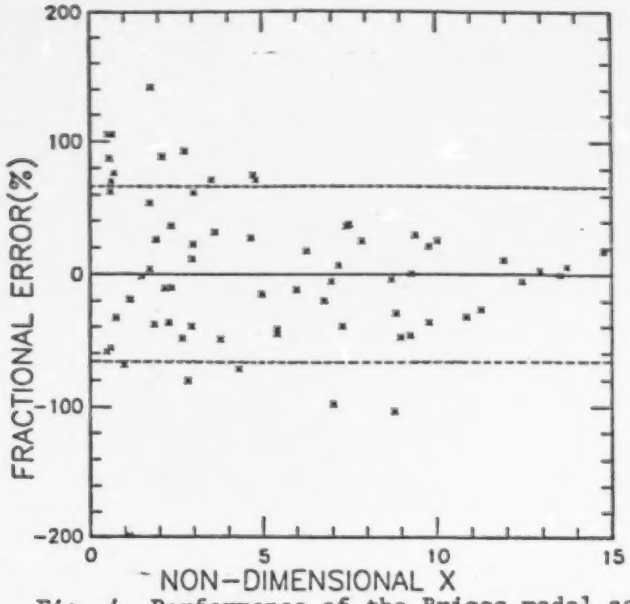


Fig. 4. Performance of the Briggs model as compared to Kincaid observations as a function of non-dimensional downwind distance.

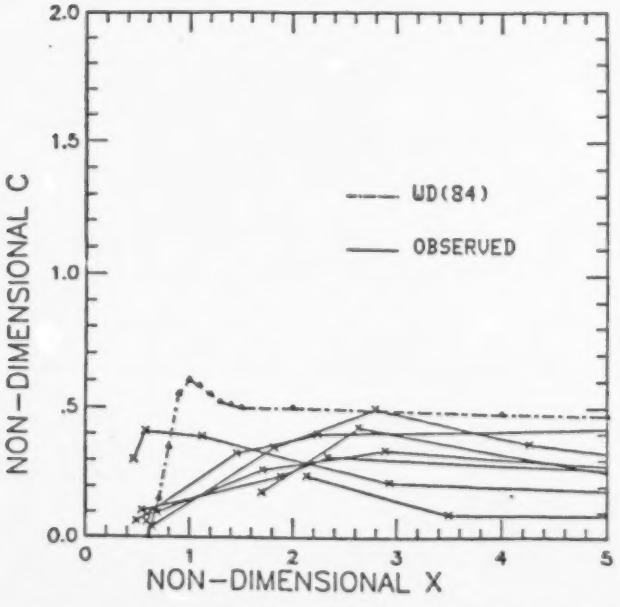
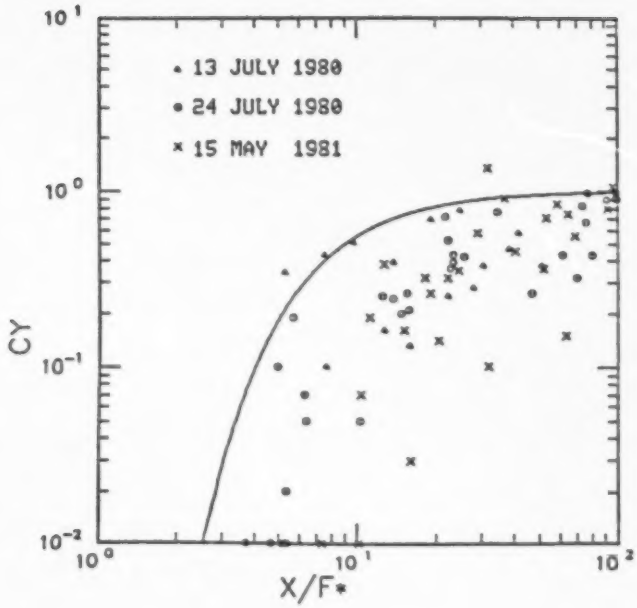


Fig. 5. Downwind variation of observed non-dimensional concentrations from the Kincaid data for F* values from 0.09 - 0.15. Dashed line is based on the Deardorff and Willis (1984) towing tank data.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